A WIDE-SENSE WAVELENGTH DIVISION MULTIPLEXED (WDM) CROSS-CONNECT DEVICE

TECHNICAL FIELD OF THE INVENTION

5   The present invention relates to communications and, more particularly, to a

wavelength division multiplexed (WDM) cross-connect device for use in optical

networks.

BACKGROUND OF THE INVENTION

A wavelength division multiplexed (WDM) cross-connect device, hereinafter

10   referred to as a WDM cross-connect, is a network of fibers connected to various optical

components that allow a set of input fibers to be connected to a set of output fibers. Each

fiber in the network can support some fixed number n of wavelength channels. In other

words, at any time there can be up to n signals along a fiber with each signal using a

distinct wavelength. WDM cross-connects are capable of performing wavelength

15   interchanging by connecting a wavelength channel on an input fiber to a different

wavelength channel on an output fiber. WDM cross-connects comprise components that

are capable of switching an incoming wavelength channel onto any different wavelength

channel on an outgoing fiber. These components are commonly referred to as

wavelength interchangers.

20   Another type of component comprised by WDM cross-connects is known as an

optical switch. An optical switch has an arbitrary number of fibers passing into it and out

of it and any wavelength channel on any incoming fiber can be switched to the same

wavelength channel on any outgoing fiber, assuming the wavelength channel is not

already being used. The WDM cross-connect also comprises optical fibers that are

connected to the optical switches and to the wavelength interchangers at nodes. The optical fibers provide directed paths through the WDM cross-connect in the sense that the signal on any optical fiber only travels in a forward direction through the cross-connect and can never meet itself.

5   When a request for a connection in a WDM cross-connect is made, the WDM cross-connect must perform two fundamental tasks. First of all, a route or path must be found in the WDM cross-connect from the requested input fiber to the requested output fiber. Secondly, for each fiber in the route, an unused wavelength channel must be assigned so that (1) the wavelength channels assigned on the input and output fibers are

10   the requested wavelength channels, and (2) the wavelength channels assigned on any two consecutive fibers in the route are the same, unless there is a wavelength interchanger connecting the two consecutive fibers.

WDM cross-connects have been proposed that have "non-blocking" properties. The term "non-blocking" corresponds to the ability of the WDM cross-connect to satisfy

15   requests for connections, i.e., the requests are not "blocked" as a result of an unavailable route or wavelength channel. Some of these WDM cross-connects are rearrangeably non-blocking, which means that satisfying requests for new connections may require changing the paths and/or the wavelength channels of already-configured connections. In a WDM cross-connect, disrupting connections in order to create new connections is

20   undesirable since doing so requires buffering of the connections that are to be rearranged.

A WDM cross-connect is considered to be pathwise rearrangeably non-blocking in cases where connection requests can be routed through the cross-connect, but any additional requests received after routing the original set of requests may require some of

the previously routed requests to be re-routed. Some WDM cross-connects are considered to be pathwise wide-sense non-blocking. These WDM cross-connects employ a routing algorithm that enables any sequence of connection requests and withdrawals to be satisfied without disturbing any of the currently routed requests. Pathwise strictly

5   non-blocking cross-connects are known that enable any set of requests to be routed through the cross-connect without disturbing the routes associated with previous requests.

A request for a connection requires not only a route from the input fiber to the output fiber, but also a wavelength channel assignment along the route that only changes wavelength channels at wavelength interchangers and that begins and ends on the

10   requested wavelength channels. These requests for connections between wavelength channels on input and output fibers are commonly referred to as demands. When a demand is made following a previously routed demand, the routes and/or the wavelength channel assignments associated with the previously routed demands may need to be changed. The definitions of wavelength rearrangeably non-blocking, wavelength wide-

15   sense non-blocking and wavelength strictly non-blocking are analogous to the definitions provided above for pathwise rearrangeably non-blocking, pathwise wide-sense non-blocking and pathwise strictly non-blocking, respectively.

A WDM cross-connect that is both pathwise and wavelength wide-sense non-blocking will be referred to hereinafter as a wide sense non-blocking WDM cross-

20   connect. Although WDM cross-connects are known that are wide sense non-blocking WDM cross-connects, known designs require a relatively large number of wavelength interchangers. Since a substantial portion of the costs associated with WDM cross-connects is attributable to the costs of the wavelength interchangers, it would be desirable

to provide a wide sense non-blocking WDM cross-connect that utilizes a minimum

number of wavelength interchangers.

FIG. 1 is a block diagram of a WDM cross-connect 1 that is commonly referred to

as a standard design WDM cross-connect. The fabric 2 between the input optical fibers 3

5   and the output optical fibers 4 of the WDM cross-connect 1 includes a plurality of nodes

(not shown) and a plurality of optical fibers (not shown) that interconnect the nodes.

Each of the nodes is comprised of a wavelength granularity switch that switches signals

received by the fabric 2 on the input fibers 3 onto selected output fibers 4. The WDM

cross-connect 1 comprises a controller 6 that controls the operations of the fabric 2 and of

10   the wavelength interchangers 5. The controller 6 causes the wavelength granularity

switches to select an appropriate output fiber 4 so that the wavelength of the signal routed

onto the output fiber 4 will not be the same as the wavelength of a signal that already

exists on the output fiber 4.

The WDM cross-connect 1 comprises k wavelength interchangers 5, where k is a

15   positive integer equal to the number of input fibers 3 and output fibers 4. Each

wavelength interchanger 5 is connected to a single input fiber 3. Each input fiber 3 is

capable of simultaneously carrying signals at n wavelengths, λ_1 through λ_n, where λ

denotes wavelength and n is a positive integer. Therefore, each input fiber supports n

wavelength channels. Each of the wavelength interchangers 5 is capable of permuting

20   the wavelength of a signal on the input fiber 3 to a different wavelength. The fabric 2

then causes the signal to be routed onto a selected output fiber 4. The controller 6

controls the selection of the wavelength channels by the wavelength interchangers 5.

Fig. 2 is a block diagram of a WDM cross-connect 7 that is commonly referred to as a modified standard design WDM cross-connect. The WDM cross-connect 7 is a modification of the design shown in Fig. 1 and includes a wavelength interchanger 8 connected to each of the output fibers 4. The WDM cross-connect 7 comprises 2k

5   wavelength interchangers. The additional wavelength interchangers 8 connected to the output optical fibers 4 enable the wavelength channel utilized by a signal on any of the output optical fibers 4 to be permuted. This enables demands to be handled that specify a particular output wavelength, which is not the case with the WDM cross-connect 1 shown in Fig. 1.

10   The additional wavelength interchangers 8 provide the WDM cross-connect 7 with improved versatility. However, 2k wavelength interchangers are utilized by the WDM cross-connect 7, which significantly increases the cost of the cross-connect in comparison to the cost associated with the cross-connect shown in Fig. 1. The cross-connects 1 and 7 are, at best, rearrangeably non-blocking and require a large number of

15   wavelength interchangers.

Accordingly, a need exists for a wide-sense non-blocking WDM cross-connect design that minimizes the number of wavelength interchangers that are needed to provide the WDM cross-connect with wide-sense, non-blocking properties.

20   **SUMMARY OF THE INVENTION**

The present invention provides a wide-sense, non-blocking WDM cross-connect that utilizes a relatively small number of wavelength interchangers. The cross-connect of the present invention comprises first, second and third fabrics and a controller that

performs a routing algorithm. The controller is in communication with each of the

fabrics and with the wavelength interchangers and performs a routing algorithm that

ensures that any sequence of connection requests and withdrawals can be routed without

disturbing any currently routed requests.

5   The first and second fabrics are interconnected by the wavelength interchangers

and by optical fibers, which connect wavelength interchangers to the first and second

fabrics. The first fabric receives input fibers, each of which is capable of simultaneously

carrying multiple signals at different wavelengths, and has output optical fibers that

connect output ports of the first fabric to the wavelength interchangers. The second

10   fabric has input ports that are connected to the wavelength interchangers by input optical

fibers. Output ports of the second fabric are connected to output optical fibers of the

second fabric, each of which are capable of simultaneously carrying multiple signals at

different wavelengths.

The third fabric is connected to the input optical fibers of the first fabric and to the

15   output optical fibers of the second fabric. For any signals carried on the input optical

fibers of the first fabric that do not require a change in wavelength, these signals are

routed through the third fabric. Since the wavelengths of these signals do not require a

change in wavelength, no wavelength interchangers are required to process these signals.

Therefore, by using this third fabric to route signals that do not require a change in

20   wavelength, the overall number of wavelength interchangers required by the WDM cross-

connect to render it wide-sense, non-blocking is decreased.

These and other features and advantages of the present invention will become

apparent to those skilled in the art from the following description, drawings and claims.

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BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a block diagram of a WDM cross-connect that is known as a standard design cross-connect.

5   Fig. 2 is a block diagram of a WDM cross-connect that is known as a modified standard design cross-connect.

Fig. 3 is a block diagram of the wide sense non-blocking WDM cross-connect of the present invention in accordance with the preferred embodiment.

10   ## DETAILED DESCRIPTION OF THE INVENTION

Prior to describing the WDM cross-connect of the present invention, the variables that are typically used to describe the properties of a WDM cross-connect will be defined. A detailed discussion of the WDM cross-connect of the present invention will then be provided, which will include a proof that utilizes these variables and that demonstrates

15   the wide-sense, non-blocking nature of the WDM cross-connect of the present invention.

A k x k WDM cross-connect that supports n > 1 wavelengths may be defined as a directed acyclic graph $C = (V, A, \Lambda)$ where V is the set of nodes, A is the set of arcs between the nodes, $\Lambda = \{\lambda_1, \lambda_2, ..., \lambda n\}$ is the set of available wavelengths, and k is an integer equal to the number of input and output fibers. An arc is typically viewed as

20   corresponding to a fiber having a single direction along which signals are permitted to flow. The node set V is partitioned into four subsets, namely, the set of input nodes, I, the set of output nodes, O, the set of optical switches, S, and the set of wavelength interchangers, W. Sets I and O each contain k nodes. Each node in the set I has an

indegree of 0 and an outdegree of 1 whereas each node in set O has an outdegree of 0 and

indegree of 1. An arc directed out of a node in set I corresponds to an input fiber and an

arc directed into a node in set O corresponds to an output fiber. A node in set W has an

indegree 1 and an outdegree 1 whereas the indegree and outdegree of a node in set S are

5   unconstrained, although in current practice they are likely to have an input degree and an

output degree equal to 2.

The topology of a cross-connect as given by the directed acyclic graph is typically

referred to as the fabric of the cross-connect. However, this definition of the fabric

assumes that the wavelength interchangers are part of the fabric. In accordance with the

10   present invention, the fabric is considered to be separate from the wavelength

interchangers. Therefore, in accordance with the present invention, the fabric should be

considered as including the optical switches, the optical fibers and the nodes, which

correspond to the locations where the optical fibers connect to the optical switches. It

should be noted that this definition of the fabric is being used herein for illustrative

15   purposes to describe the various aspects of the present invention.

A demand, d, is defined as a 4-tuple (w, x, y, z), where w is an input node, x is a

wavelength, y is an output node and z is a wavelength. The wavelengths x and z will be

referred to as the input and output wavelengths, respectively. A route, r, in C is a

directed path from a node in set I to a node in set O. Along each of the fibers in a route r,

20   one of the n wavelengths is assigned such that consecutive fibers are assigned the same

wavelength, unless the common node of the fibers is in set W. A route for a demand d =

(w, x, y, z) is a route from input node w to output node y such that, on the corresponding

input fiber, the route is assigned wavelength x and on the corresponding output fiber, the route is assigned wavelength z.

A valid demand set is a set of demands that satisfies the following conditions:

(i) for each input node, a, and each wavelength, λ, there is at most one demand

5   with both a as the input node and λ as the input wavelength; and

(ii) for each output node, b, and each wavelength, λ, there is at most one demand

with both b as the output node and λ as the output wavelength.

A demand set $D = \{d_1, d_2, ..., dm\}$ is said to be satisfied by a cross-connect if

there exists a set of routes $R = \{r_1, r_2, ..., r_m\}$ where:

10   (i) r_i is a route for d_i, $1 \leq i \leq m$; and

(ii) if for some value $i \neq j$, r_i and r_j share some fiber, f, then they must be assigned

distinct wavelengths along fiber f.

Such a route set, R, is referred to as a valid routing of the demand set D, and R is

said to satisfy D. A wavelength interchanger, WI_i, services a particular demand, d_i, if the

15   demand d_i is routed through wavelength interchanger WI_i.

A discussion of the WDM cross-connect 10 of the present invention will now be

provided with reference to Fig. 3. In accordance with the present invention, the fabric of

the cross-connect 10 comprises three parts 11, 12 and 19. Parts 11 and 12 are

interconnected by one or more wavelength interchangers 13. Part 19 is connected to the

20   input fibers 14 and to the output fibers 16. The three parts 11, 12 and 19 will be referred

to hereinafter as fabric F1, fabric F2 and fabric F3. The fabrics F1, F2 and F3 comprise

the optical switches and the optical fibers that are connected to the optical switches at

nodes of the fabrics. Therefore, the fabrics themselves F1, F2 and F3 can be viewed as not including any devices for changing the wavelength of any signal.

The operations of the WDM cross-connect 10 are controlled by the controller 15, which may be, for example, a microprocessor programmed with appropriate software to

5   execute the routing algorithm of the present invention. Each of the fabrics F1, F2 and F3 can be any WDM cross-connect fabric that has a topology of any wide-sense or strictly non-blocking cross-connect. For example, each cross-connect could have a cross-bar design. Any demand whose input and output wavelengths differ will be routed through F1 11 to some wavelength interchanger 13 and then through F2 12. Any demand whose

10   input and output wavelengths are the same will be routed from a corresponding input optical fiber 14 of the first fabric F1 11 through fabric F3 19 and output onto an output optical fiber 16 of fabric F2 12.

Since F1, F2 and F3 can be based on standard wide-sense, non-blocking cross-connects, known algorithms A1, A2 and A3 exist for routing through F1, F2 and F3,

15   respectively. Therefore, the routing algorithm of the present invention will only need to determine which wavelength interchanger 13 to route a demand through or which demand is to be routed through fabric F3 19. The algorithms A1 and A2 and A3 may then be used as subroutines to route demands through the fabrics in the WDM cross-connect 10.

20   Since full wavelength interchangers (i.e., devices that can change the wavelength of all signals entering it) are currently, and are likely to remain, complicated and expensive devices, simpler devices that permit wavelength interchange amongst only a small number of wavelengths are of interest. Thus, the problem of designing optimal

wide-sense, non-blocking WDM cross-connects for the case where there are only two or three available wavelengths will now be discussed. In order to demonstrate the concepts of the present invention, it will be shown that a wide-sense WDM cross-connect can be designed that uses fewer wavelength interchangers than would be required for a similar

5   strictly non-blocking WDM cross-connect.

Showing that the WDM cross-connect of the present invention is a wide-sense, non-blocking WDM cross-connect can be demonstrated by showing that there is a wavelength interchanger available for any new demand. First, it is assumed that the WDM cross-connect comprises $2k - 1$ wavelength interchangers 13 and that new demand

10   d exists of type (x, y). When this demand is made, there can be, at most, $k - 1$ existing demands using input wavelength x and $k - 1$ other existing demands using output wavelength y. In the worst case, therefore, each demand uses its own wavelength interchanger. This means that there are, at most, $2k - 2$ wavelength interchangers that are blocked from servicing the new demand. Therefore, if the WDM cross-connect 10

15   comprises $2k - 1$ wavelength interchangers, then there must be one that can service the new demand. This is true even if the WDM cross-connect 10 does not use any algorithm for routing the demands. This gives rise to the question of whether or not fewer than $2k - 1$ wavelength interchangers can be used if an algorithm is used to route the demands, which would enable the wavelength interchangers to be used more wisely.

20   In accordance with the present invention, it has been determined a k x k wide-sense, non-blocking WDM cross-connect can be designed that utilizes only 2 wavelengths (i.e., colors) and which requires only k wavelength interchangers. At least k wavelength interchangers are required since k demands that each require a change from a

wavelength λ_1 to a wavelength λ_2 could occur. Therefore, each demand would need its

own wavelength interchanger. Similarly, since, in the present example, there are only

two types of demands (i.e., those that change from λ_1 to λ_2 and those that change from λ_2

to λ_1), each of k wavelength interchangers could service one of each type of such

5   demands. That is, any routing algorithm that routes any demand whose input and output

wavelengths differ through any of the available wavelength interchangers, and that routes

any demand whose input and output wavelengths are the same through F3, is a routing

algorithm that will always succeed. Thus, for a k x k WDM cross-connect, k wavelength

interchangers are both necessary and sufficient for the case of 2 colors (i.e., 2

10   wavelengths).

It will now be shown that a routing algorithm can be used that ensures using 8k/5

wavelength interchangers in a cross-connect of the design shown in Fig. 3 will result in a

wide-sense, non-blocking WDM cross-connect in the case where there are three

wavelengths. It is assumed here that three wavelengths are r, g and b are used. It will be

15   shown that if *express routes* exist, which means that if there is a (r, r), (b, b) or (g, g)

demand, then the WDM cross-connect 10 can route these demands without using a

wavelength interchanger. The manner in which a determination can be made as to an

upper bound on the number of wavelength interchangers that are needed for a wide-sense,

non-blocking k x k cross-connect will now be discussed.

20   Demands of type *(b, g)*, *(g, r)* and *(r, b)* will be defined herein as Class A

demands and demands of type *(g, b)*, *(r, g)* and *(b, r)* will be defined herein as Class B

demands. The phrase *class(d) = A* is used herein to indicate that demand d is a *class A*

demand. The phrase *class (d) = B* is used herein to indicate that demand d is a *class B*

demand. Constraints C_A and C_B are defined to mean that there are fewer than $7k/5$ wavelength interchangers that service a *class A* demand and $7k/5$ wavelength interchangers that service a *class B* demand, respectively. This assumes that there are only $8k/5$ wavelength interchangers available in the WDM cross-connect 10.

5   The motivation for defining constraints C_A *and* C_B is to demonstrate that, if there is a wavelength interchanger that is servicing *class A* demands, then it can be used to serve new *class A* demands (i.e., demands of a type other than those it is already servicing). However, if these were the only constraints considered, problems relating to withdrawals might not be handled. Stating the problem this way requires the re-use of

10   wavelength interchangers already servicing the same class of demands (as desired), while avoiding problems that might result from withdrawals.

Thus, the proof is as follows: Letting $W(x, y)$ be the set of wavelength interchangers that service a type (x, y) demand, $x, y \in \{r, b, g\}$ and letting $w(x, y) = |W(x, y)|$, constraints $C((x, y), (y, z))$, where $x, y, z \in \{b, r, g\}$, are defined as

15      $$C((x, y), (y, z)): \ w(x, y) + w(y, z) - |W(x, y) \cap W(y, z)| \le 6k/5.$$

Such a constraint requires that the number of wavelength interchangers that service a type (x, y) demand and/or a type (y, z) demand is no more than $6k/5$. Six kinds of these constraints exist.

The motivation for the $C((x, y), (y, z))$ constraints is that when it is desired to

20   insert a new type (x, z) demand, it can be blocked by other type (x, z) demands, namely, by type (x, y) demands or type (y, z) demands. Thus, if there are, at most, $6k/5$ total of the latter two blockages, then there can be at most $2k/5$ remaining type (x, z) demands, which would need, at most, $8k/5$ wavelength interchangers to handle them.

Demands d1 and d2 are said to be mirror opposite demands if d1 is a type (x, y) demand and d2 is a type (y, x) demand, where x is one of r, b, or g and y is one of r, b, or g, but x and y are not the same. In order to prove that this constraint can be maintained as

5 new demands are added (or withdrawn), an additional kind of constraint will be considered. Letting $E(\{g, r\})$ be the number of wavelength interchangers that are servicing mirror opposite demands of the type *(g, r)* and *(r, g)*, letting $E(\{b, g\})$ be the number of wavelength interchangers servicing mirror opposite demands of type *(g, b)* and *(b, g)*, and letting w be the number of wavelength interchangers servicing mirror opposite

10 demands of type *(b, r)* and *(r, b)*, a constraint $T(\{g, r\}, \{b, g\}$ can be defined as $E(\{g, r\})$ + $E(\{b, g\}) \le 4k/5$. For the other pairs of mirror demands, analogous constraints can be defined.

Then, the routing algorithm of the present invention is as follows: Route any new demand so that all constraints mentioned above are maintained. It will now be proven

15 that such a set of constraints can always be maintained. That is, it will be shown that a routing algorithm can be created that will always be able to find a routing that does not violate any of the constraints. It will now be shown that these constraints can always be maintained when new demands are presented. Throughout this proof, it will be assumed that a given a type *(b, g)* demand d is to be inserted.

20 Let A be the set of wavelength interchangers that service a type *(g, r)* demand but no other class A demand, B be the set of wavelength interchangers that service a type *(r, b)* demand but not other class A demand, C be the set of wavelength interchangers that service a type *(b, g)* demand (they can also service other class A demands) and D be the

set of wavelength interchangers that service a type *(g, r)* and a type *(r, b)* demand but no

type *(b, g)* demand. Define $\alpha = |A|$, $\beta = |B|$, $\gamma = |C|$ and $\delta = |D|$.

The C_A constraint could be forced to be violated if $\alpha + \beta + \gamma + \delta = 7k/5$ and all

these wavelength interchangers are blocked so that the WDM cross-connect 10 is

5   prevented from routing the new type *(b, g)* demand through them. Then, each

wavelength interchanger in A must also be servicing a mirror opposite demand of type *(r,*

g) and every wavelength interchanger B must be servicing a type *(b, r)* demand.

However, for a wavelength interchanger in D to be blocking a type *(b, g)* demand, it must

already be servicing a type *(b, g)* demand, but this contradicts the definition of D. Thus,

10    $\delta = 0$ (i.e., *D = 0)*.

Every wavelength interchanger in A and C services a demand with output

wavelength g (before d is routed) and so $\alpha + \gamma < k$. Every wavelength interchanger in B

and C service demands with input wavelength b and so $\beta + \gamma < k$. Also, the total number

of wavelength interchangers in A and B is inductively assumed to be bounded to be no

15   more than 4k/5 since it has been assumed that $T(\{g,\ r\},\ \{r,\ b\})$ holds true. That is, $\alpha + \beta \leq$

4k/5. Adding these three inequalities results in the following:

$$2(\alpha + \beta + \gamma) < 14k/5.$$

Therefore, $\alpha + \beta + \gamma < 7k/5$, and this contradicts the assumption that $\alpha + \beta + \gamma + \delta = 7k/5$

(since $\delta = 0$).

20   Now, it will be shown that the $T(\{g,\ r\},\ \{b,\ g\})$ kind of constraints never need be

violated either. Supposing that $E(\{g,\ r\}) + E(\{b,\ g\}) = 4k/5$, and a new type *(b, g)*

demand d must be routed. Supposing there are some available wavelength interchangers

that are currently servicing a type *(g, b)* demand and that $T(\{g,\ r\},\ \{b,\ g\})$ would be

violated if demand d is routed through one of them. Thus, these wavelength

interchangers can be thought of as being "blocked" from being used for routing d since

that would cause the constraint to be violated. It will now be considered what could

prevent routing d through some wavelength interchanger other than those servicing a type

5   (g, b) demand.

A wavelength interchanger might be servicing a type (b, r) demand or a type (r, g)

demand, and that would block the routing of d through it. Supposing there are a total of s

wavelength interchangers blocked by any of these three types of demands. However, all

of these types of demands are from class B and it has been shown that there are already

10   4k/5 wavelength interchangers servicing class B demands (namely, the 4k/5 wavelength

interchangers servicing the $E(\{g, r\}) + E(\{b, g\}) = 4k/5$ mirror opposite demands).

Therefore, there are no more than 8k/5 – 7k/5 = k/5 wavelength interchangers

unaccounted for so far. Of course, there could be some number, t, of wavelength

interchangers blocked by demands of type (b, g) (the same type as d), but since the $E(\{g,$

15   $r\}) + E(\{b, g\}) = 4k/5$ wavelength interchangers blocked with mirror opposite demands

all have a g output wavelength, it is known that $t < k/5$, since d also has a g output

wavelength. Therefore, less than 8k/5 wavelength interchangers have now been

accounted for, and so there must be some wavelength interchanger left over that is not

blocked (i.e., either in the usual sense or in the sense that routing d through it would

20   increase the number of wavelength interchangers servicing mirror opposite demands).

Therefore, d can be routed through one of these wavelength interchangers.

Now, the question of how the constraint $C((b, g), (g, x))$ can be violated will be

considered. Considering the $C((b, g), (g, r))$ constraint and supposing that it is about to

be violated, the number of wavelength interchangers servicing one or both of these types

of demands is 6k/5, and the demand d is blocked from going through any of them. Such

wavelength interchangers are either (i) already servicing a type *(b, g)* demand or,

otherwise, (ii) servicing a type *(g, r)* demand as well as a type *(r, g)* demand. However,

5   that would mean that there are 6k/5 > k wavelength interchangers servicing demands with

g output. Thus, the set W_1 of wavelength interchangers servicing a type *(g, r)* demand

that can also service d must be non-empty. Similarly, considering the case of the other

constraint *C((b, g), (r, b))* that d might be forced to violate, it is known that the set W_2 of

wavelength interchangers that are currently servicing a type *(r, b)* demand that are not

10   blocked from servicing d is also non-empty.

However, the question remains of whether there exists a wavelength interchanger

in $W_1 \cap W_2$. Clearly, if there is some wavelength interchanger in *D*, then it is in $W_1 \cap$

W_2. On the other hand, if it is assumed that $\delta = 0$ (i.e., *D = 0*), then $\alpha + \gamma = \beta + \gamma = 6k/5$

and $\alpha + \beta + \gamma < 7k/5$. This implies that $\gamma = k$, but since d has not been routed yet, it is

15   known that $\gamma < k$. More explicitly,

$$12k/5 = 7k/5 = 5k/5 = k$$

and thus $\gamma > 12k/5 - 7k/5 = 5k/5 = k$.

Therefore, it can be seen that the constraints C_A and C_B are relevant, the real work

is done by the *C((x, y), (y, z))* constraints, which are maintainable by maintaining the *T()*

20   constraints, since if those are maintained, it is never necessary to use more than 8k/5

wavelength interchangers. This is true since, for demand d, at most 6k/5 wavelength

interchangers are blocking it that do not service a demand of the same type as d, and at

most 2k/5 − 1 other demands of the same type as d can exist. Therefore, there is always

at least one wavelength interchanger available.

The present invention has been described with reference to the preferred

embodiments. However, those skilled in the art will understand that the present invention

5   is not limited to the embodiments explicitly described herein. Those skilled in the art will

understand that modifications may be made to the embodiments discussed above that are

within the scope of the present invention. It will also be understood that the present

invention is not limited with respect to the types of components that are used to create the

cross-connect 10 of the present invention. Those skilled in the art will understand that a

10   variety of different components may be used to produce the fabrics F1 11, F2 12 and F3

19 and the wavelength interchangers 13. Those skilled in the art will also understand that

a variety of different types of controllers may be used for the controller 15 that performs

the routing algorithm of the present invention.